Photonics

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Displays

Human vision

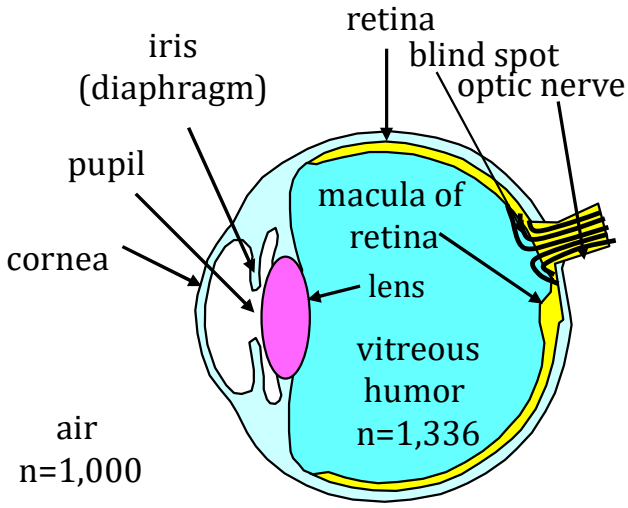
Colour and colourimetry

The eye

- Projection of the light on the retina:
  light sensitive cells

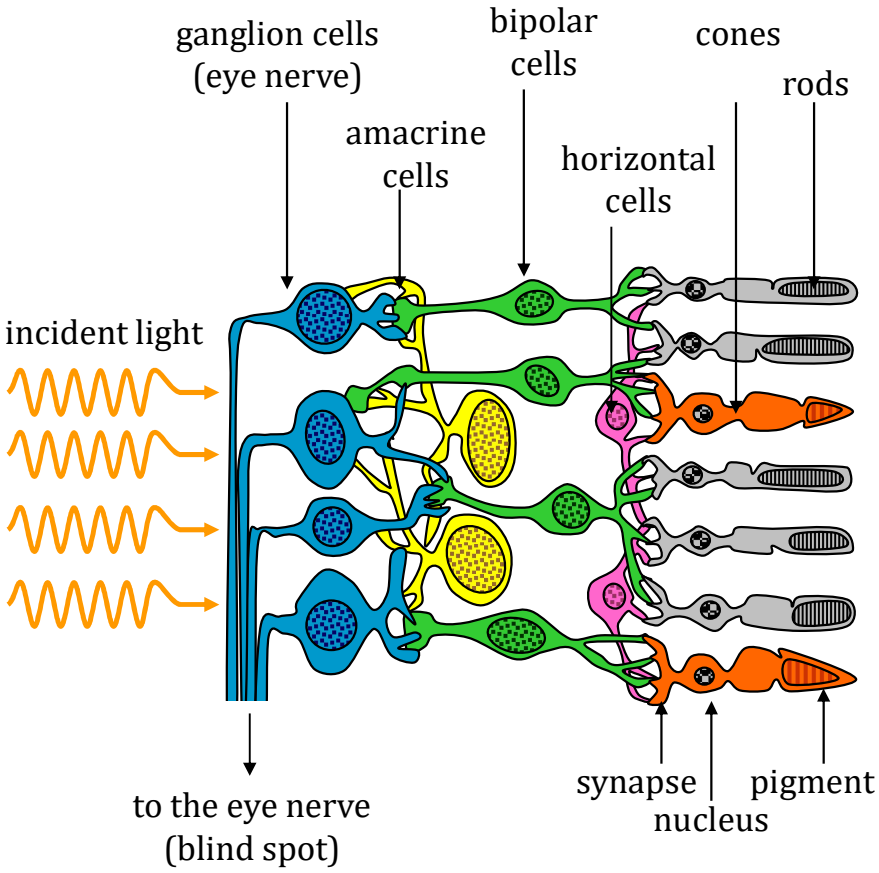
- Macula (Yellow spot): most sensitive part of the retina
  - 0.01% of the surface
  - 10% of receptors

- Blind spot:
  attachment of the eye nerves:
  no receptors



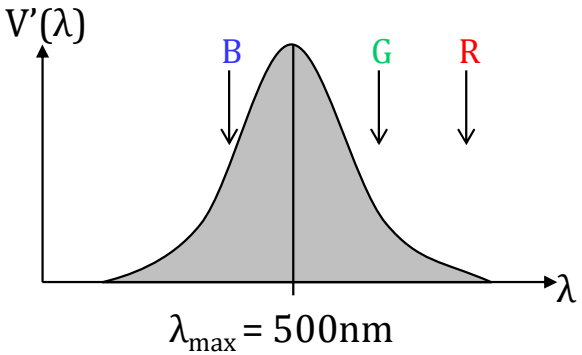
Retina

- Retina
  - different layers
  - nerves are located on the top
  - rods: intensity
  - cones: color
- 130 million receptors
  - >120 million rods
  - 6-7 million cones
- 1.2 million neurons
  - ➔ cross connections



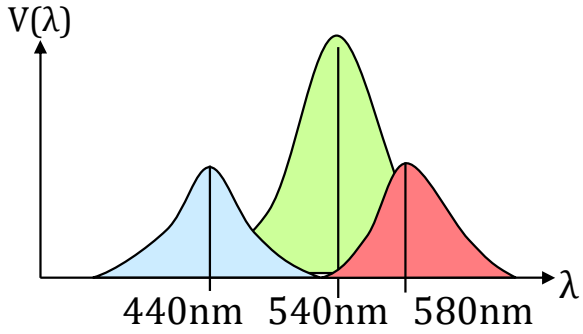
Eye spectral sensitivity curves

- Rods
  (scotopic sight /low-light)

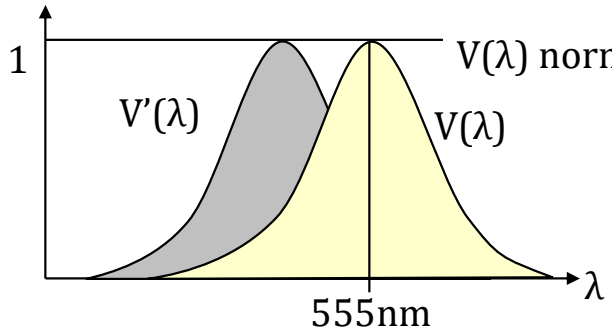


➔ poor red vision

- cones
  (photopic sight/ well-lit)



➔ 1W @ 550nm ⇔ 2W@ 610nm



V(λ) normalized to 1 @ 555nm

Lumineous flux

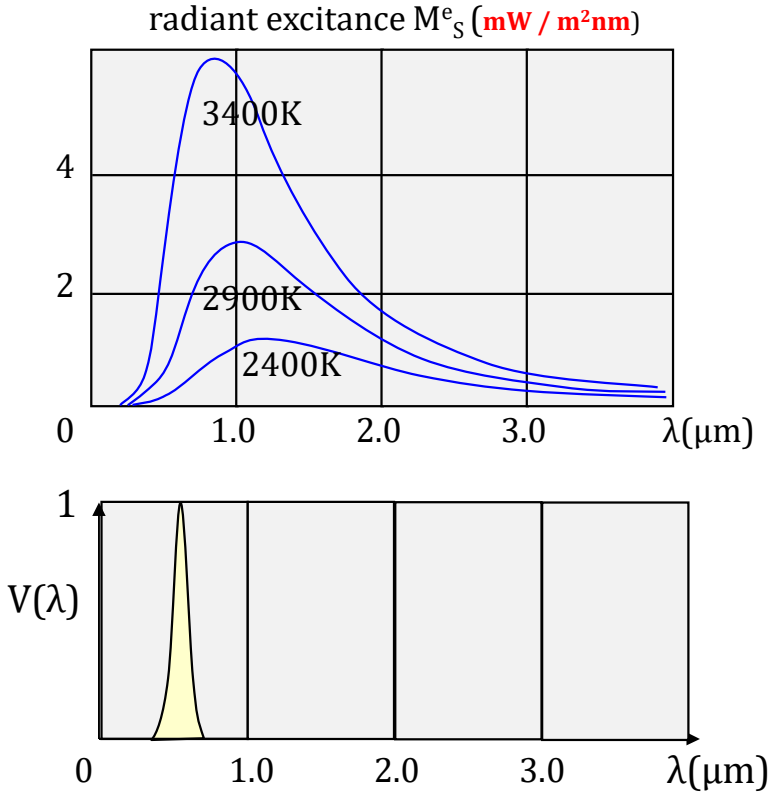
- Spectral density $F_S^e(\lambda)$:
  The amount of radiation energy per unit time per unit wavelength through a given surface area
  Units: W/m (or W/Hz for $F_S^e(\nu)$)

- Luminous flux F :
  Units: lumen

$$F = K \int_0^\infty F_S^e(\lambda) V(\lambda) d\lambda$$

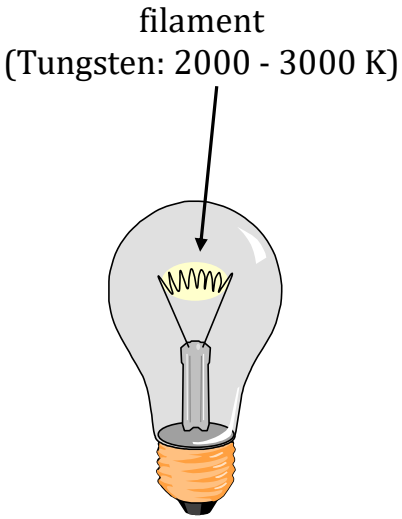
$$K \equiv 683 \frac{lumen}{Watt} (lm/W)$$

Black body radiation spectrum (per unit surface area)

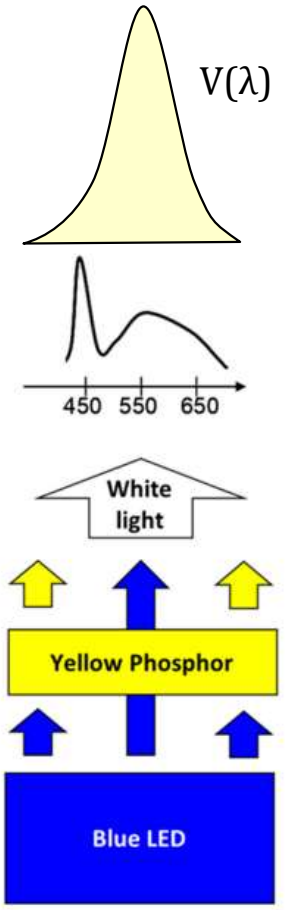


Lighting efficiency

- Incandescent lamps
  - Filament is heated by the Joule effect
  - Spectrum ~ black body radiator
  - 10 - 20 lumen / Watt input power



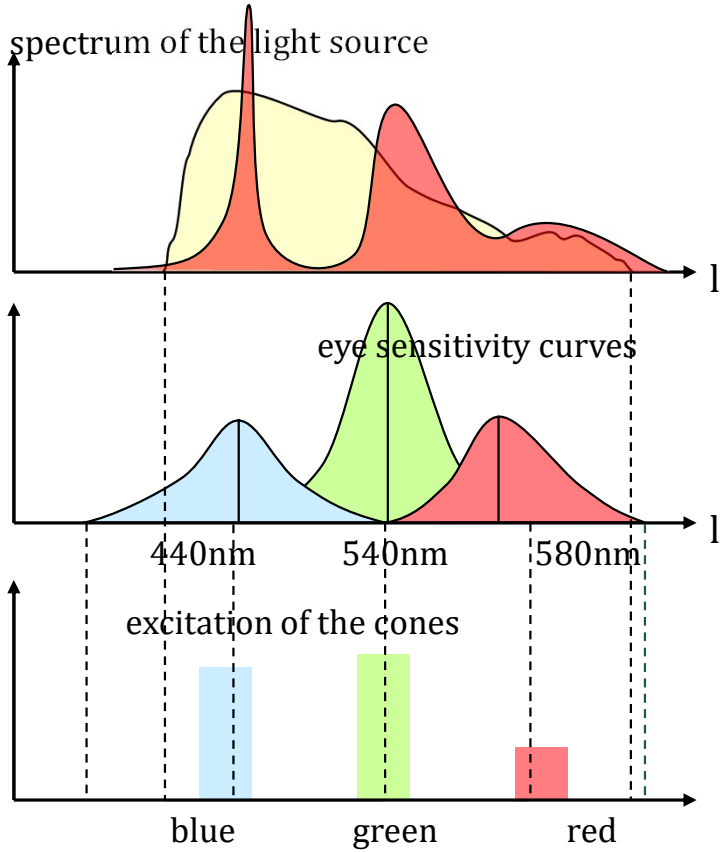
- LED lighting
  - Radiative recombination in semiconductor
  - Narrow spectrum
  - white light LED= blue LED + phosphor layer
  - 80 - 120 lumen / Watt input power



Colour perception

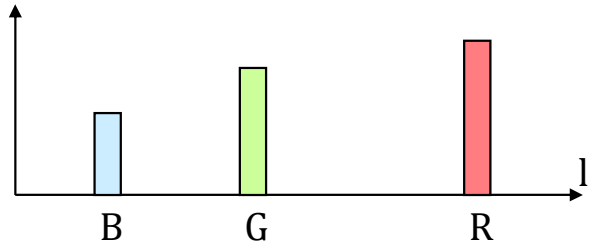
- Eye = sensitive to colours
  - doesn't detect wavelength
  - sensitivity to colours due to different cones
  - cones are excited differently
  - 3D color space
- Metameric pair
  - two spectra that excite the cones identically
- Colour perception

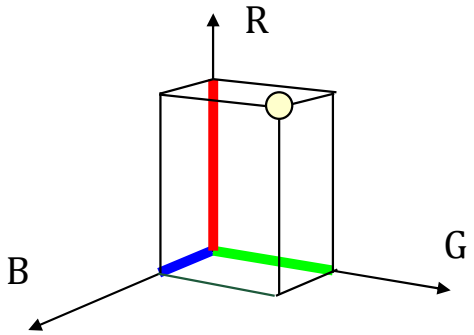
https://www.youtube.com/watch?v=l8_fZPHasdo&vl=en



Colour coordinates

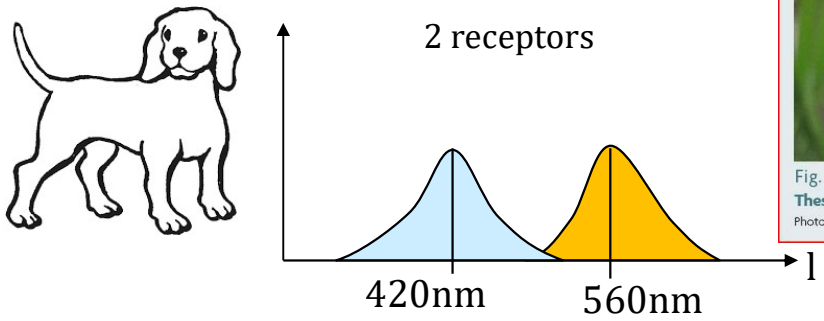
- 3 light sources with (additive) primary colours:
  - e.g. red, green, blue

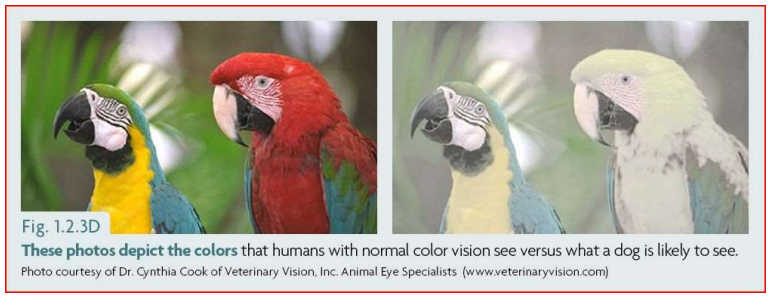




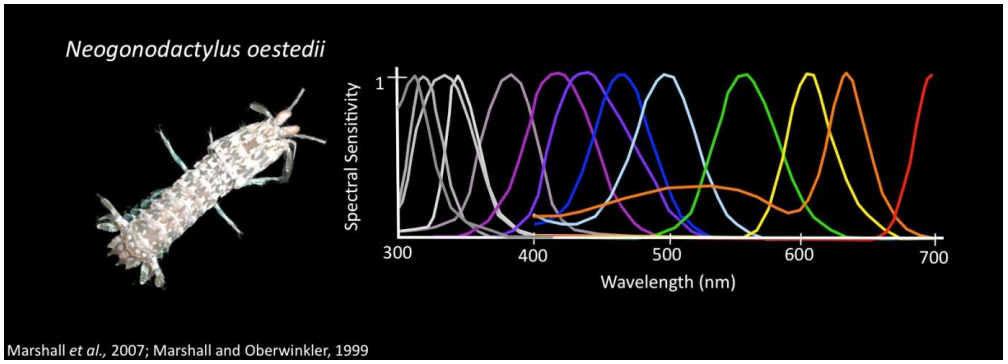
- Colour coordinates of a given colour
  = intensity of each source, which results in a given color by additive mixing
  = depends on the selected primary colours

Animal Vision





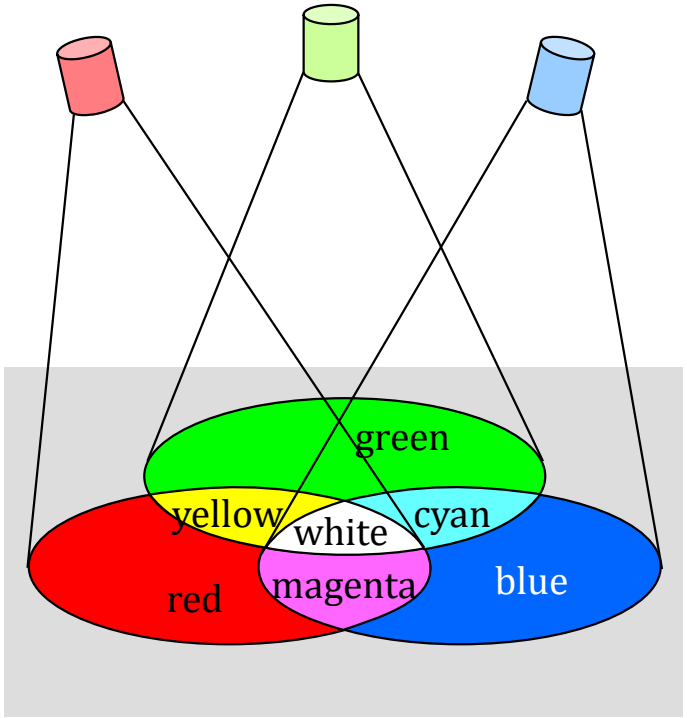
Mantis shrimp

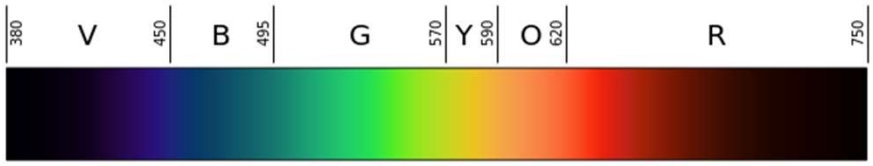


16 receptors!

https://www.photonicsonline.com/doc/mantis-shrimp-s-sophisticated-eyes-guide-novel-camera-design-0001

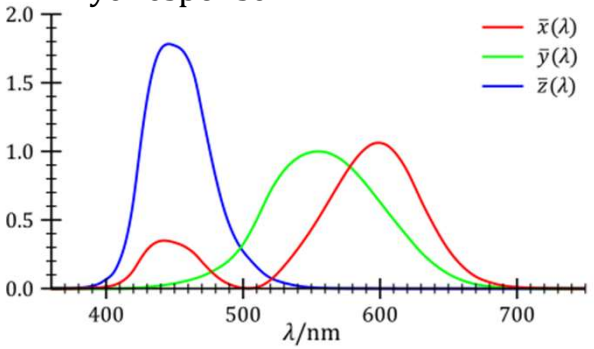
Additive color mixing



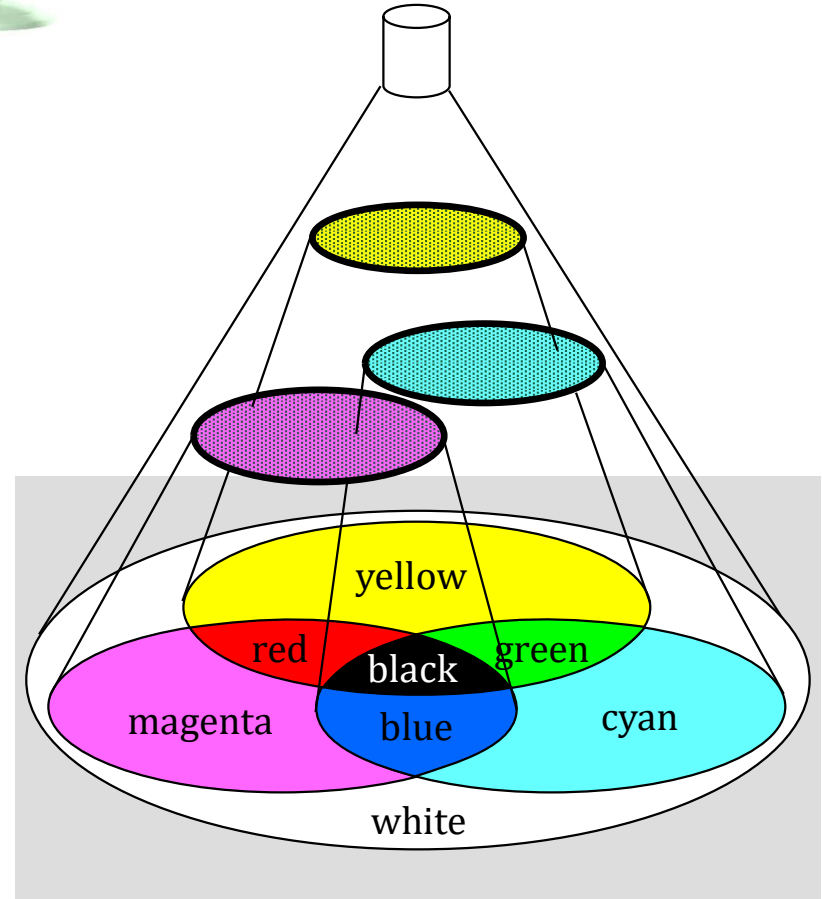


- 3 primary light sources
  - red, green, blue
  - spectrum
    ~ sensitivity of the cones
  - variable intensity
    → any color impression
- Examples:
  - stage lighting
  - TV, displays

Eye response



Subtractive colour mixing



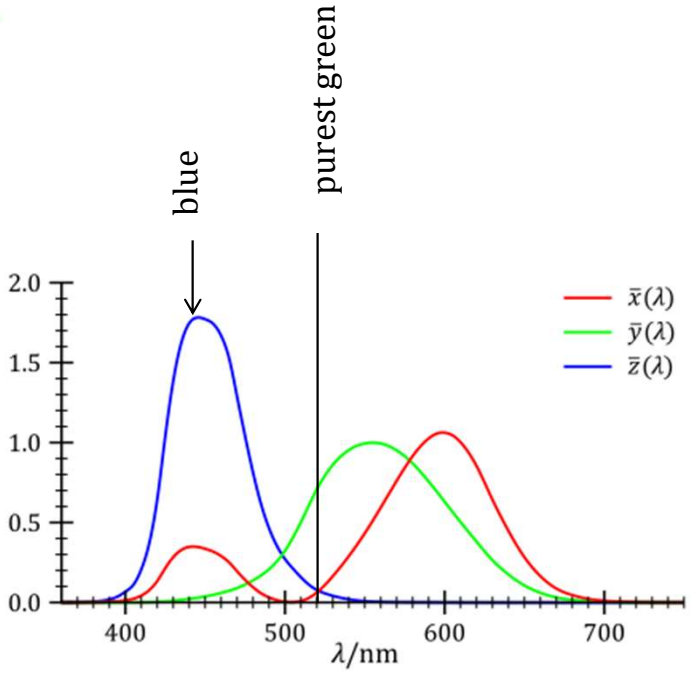
- 3 primary colours (filters)
  - yellow, cyan, magenta
  - only the spectral overlap remains
  - variable intensity
    → any color impression
- Examples:
  - reflection from an object
  - filters
  - mixing of paints
  - offset printing

Color space is a 3D linear vector space

- Light source A → coordinates R_A, G_A, B_A
- Light source B → coordinates R_B, G_B, B_B

- Light source A + Light source B
  → coordinates R_A+R_B, G_A+G_B, B_A+B_B
  - This follows from physiological observation

Colour coordinates in the CIE XYZ-system



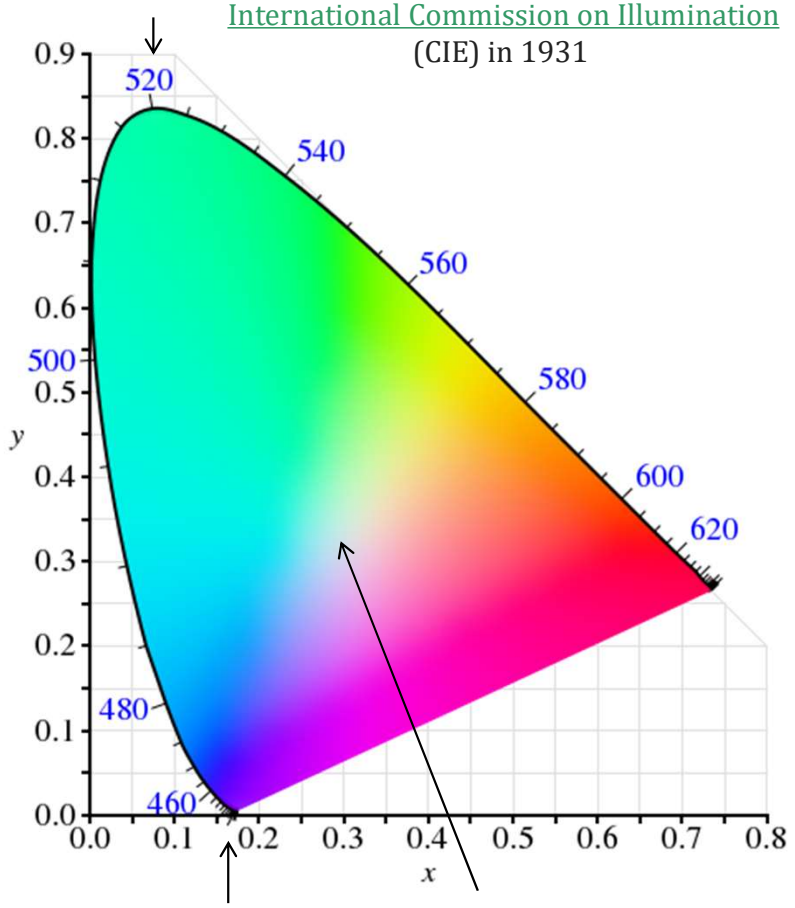
Normalization

x = X / (X+Y+Z)

y = Y / (X+Y+Z)

z = Z / (X+Y+Z)

International Commission on Illumination (CIE) in 1931

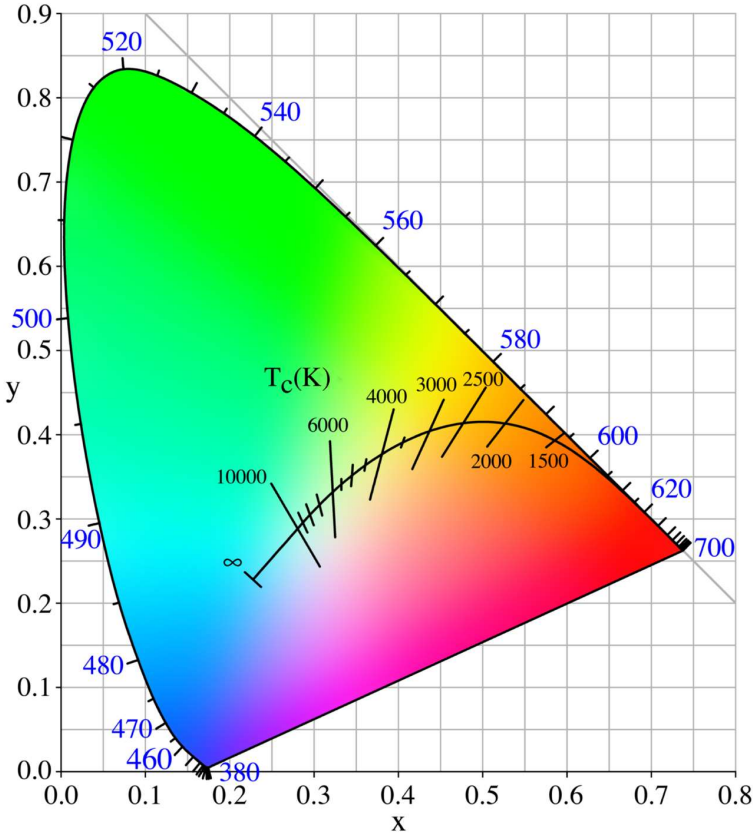


(0.33,0.33,0.33) white

Colour coordinates in the CIE XYZ-system

- Colour temperature
  - Temperature of the black body with similar color effect
  - Point on the black body line that is the closest to the source spectrum
  - Holds only for point close to the black body line

- e.g.
  the colour temperature of the color K is approx. 8000K



https://en.wikipedia.org/wiki/Planckian_locus

Colour coordinates in the CIE XYZ-system

- Hue
  = dominating spectral color

$$\text{hue} = S$$

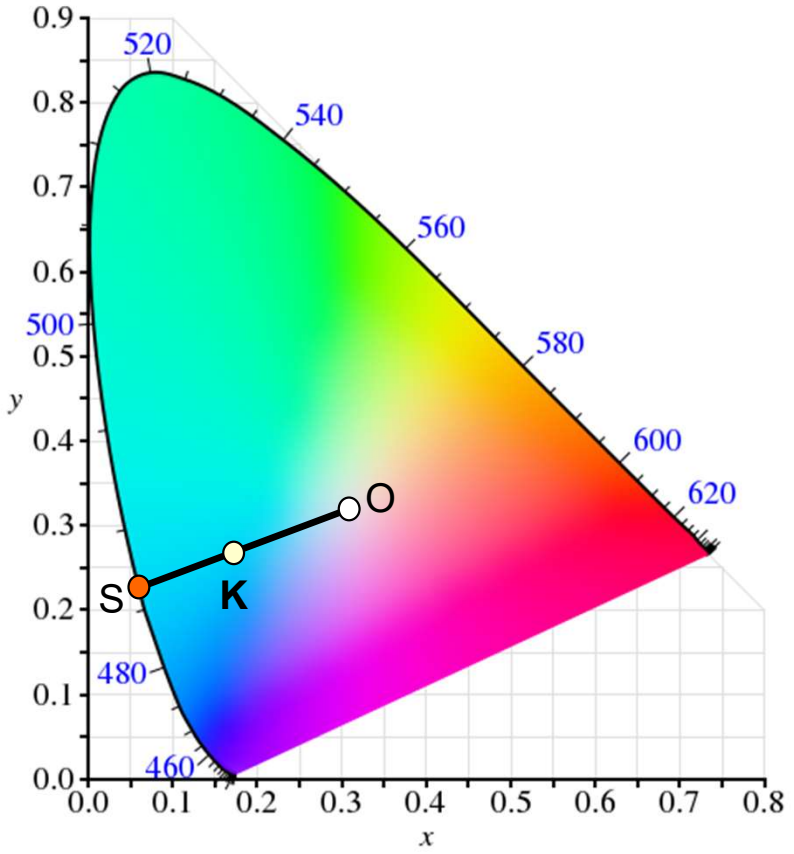
- Chroma

$$\text{chroma} = \frac{|OK|}{|OS|}$$

- Value
  = measure of darkness or brightness

$$\text{value} = Y \text{ (0-10)}$$

- the Munsell color system



Colour coordinates in the CIE XYZ-system

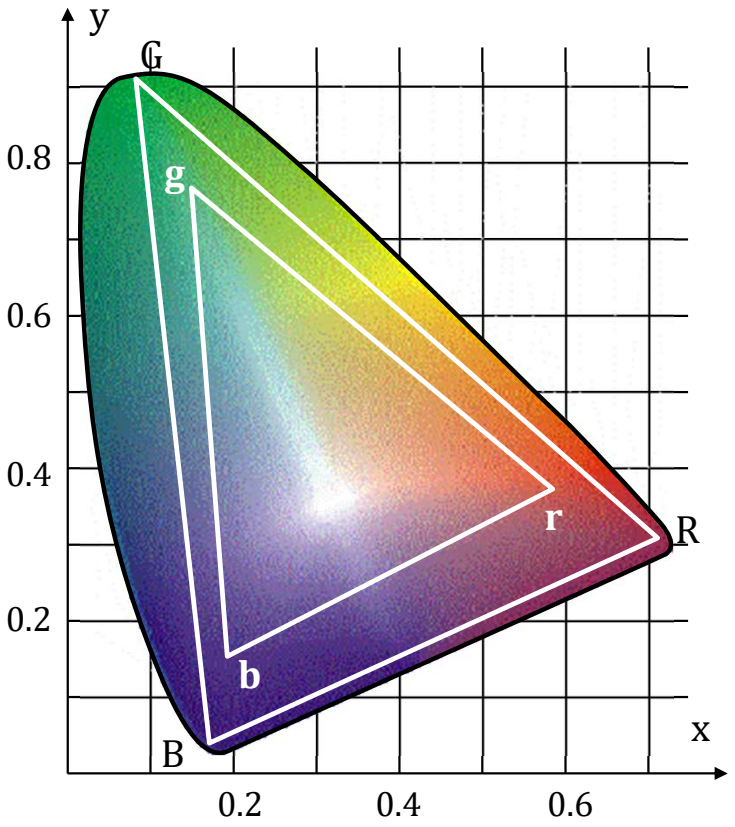
- on the edge monochromatic colors are found
- An arbitrary spectrum is a weighted sum of the points on the edge

- New color coordinates:
  - select 2 primary colors

  → any color on the line can be obtained
  - select 3 primary colors

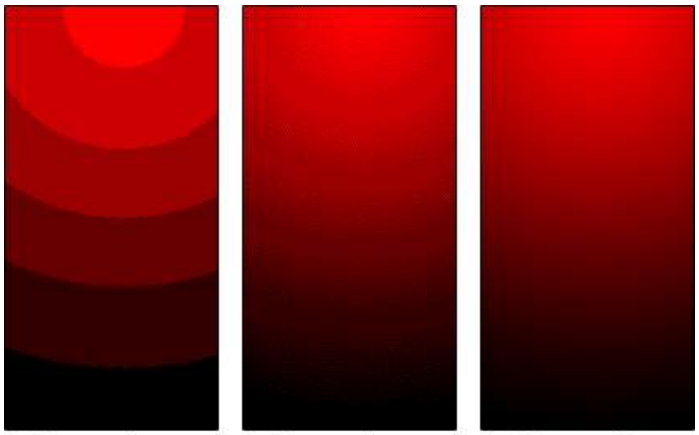
  →any color within the triangle can be obtained

- Selected primary colors should be as saturated as possible
  - RGB basis can form more colors than rgb



Colour banding in displays

- Intensity resolution



8-bit gradient | 8-bit gradient, dithered | 24-bit gradient

https://en.wikipedia.org/wiki/Colour_banding

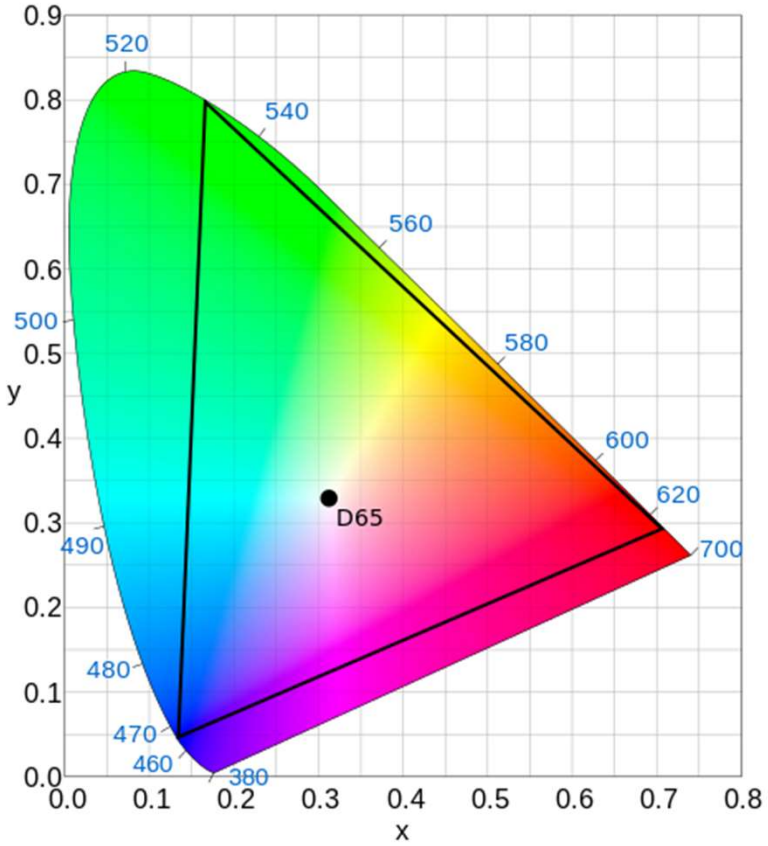
https://en.wikipedia.org/wiki/Dither

High dynamic range video

- The dynamic range in the intensity is increased (Y in the Hue, Chroma, Value system)
- Standard dynamic range is 8 bits with 64 intensity levels used
- HDR10 Media Profile
  - wide-gamut Rec. 2020 color space, bit depth of 10-bits
  - allows for display HDR video with luminance level of up to 1,000 cd/m2
- Dolby vision 12-bit color depth + metadata (use 10,000 cd/m2)

RGB color space parameters								
Color space	White point		Primary colors					
	x_W	y_W	x_R	y_R	x_G	y_G	x_B	y_B
ITU-R BT.2020	0.3127	0.3290	0.708	0.292	0.170	0.797	0.131	0.046

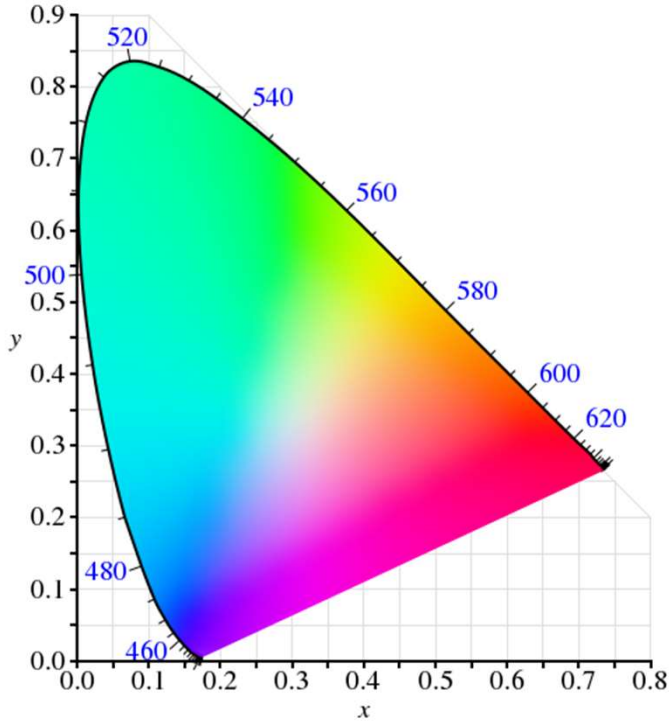
ITU-R Recommendation BT.2020



Example: Colour Perception

- From the CIE chromaticity diagram below deduce the relative excitation of the colour receptors for monochromatic light with a wavelength of 500 or 600 nm, respectively.

- Why is there no combination of monochromatic light sources that cause a response at the point (0.00, 0.00)?



Example

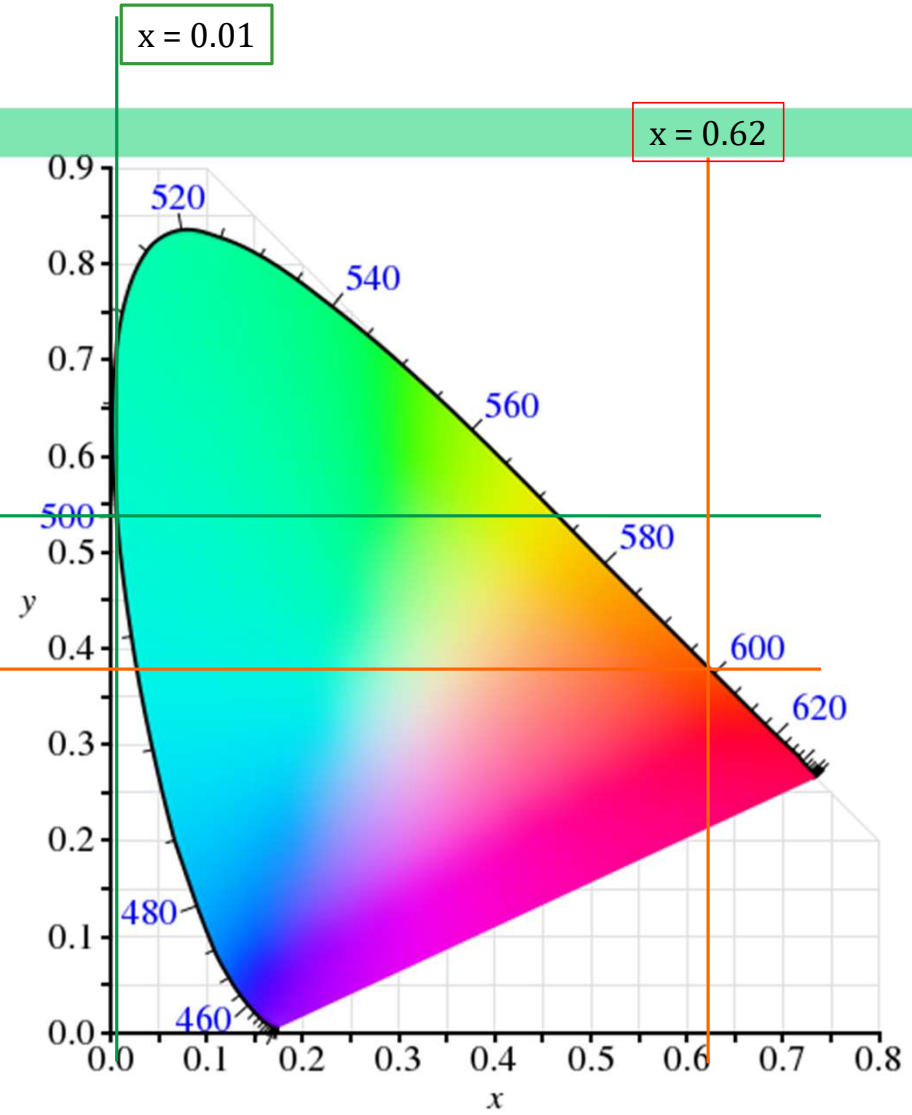
Coordinates of 500 nm or 600 nm monochromatic light

y = 0.54

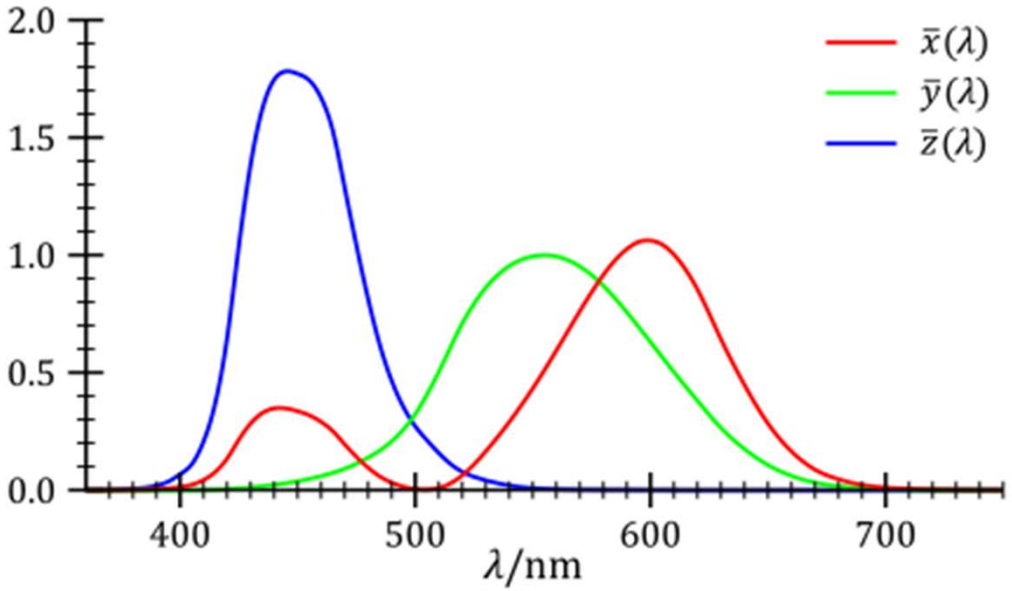
500 nm: z = 1 – 0.01 – 0.54 = 0.45

y = 0.38

600 nm: z = 1 – 0.62 – 0.38 = 0.0



Example



Why is there no combination of monochromatic light sources that cause a response at the point (0.00, 0.00)?

x = 0 & y = 0 → z = 1.0 This cannot be done

Finally

There is a lot more to photonics

IEEE Spectrum

https://spectrum.ieee.org/

IEEE

Institute of Electrical and Electronics Engineers

https://www.ieee.org//

OPTICS & PHOTONICS NEWS

https://www.optica-opn.org/

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